[22]

$$E_0(m_t) = \begin{cases} m_0 \exp\left(\int_0^t 2\frac{\dot{M}(s;T)}{M(s;T)} + \phi\left[\frac{1}{2}\phi\, M(s;T) - \delta\right] + \frac{1}{2}\phi(\phi-1)\sigma^2 ds\right) & , \; 0 \le t < T \\ E_0(m_T)\exp\left(r - \sqrt{B^2 - 4AC_{(a)}}\right)(t-T) & , \; t \ge T \end{cases}$$

where $m_0 = \frac{1}{4}\phi^2(M(0;T))^2\ \theta_0^{\phi}$

Moreover, in the case where T = 0, since $M(t;T) = M^{II}$ and M(t;T) = 0, the equation [22] reduces to:

[23] $$E_0\left[m_t\right] = m_0 \exp\left(r - \sqrt{B^2 - 4AC_{(a)}}\right)t \quad , \; t \ge 0$$

where $m_0 = \frac{1}{4}\phi^2(M^{II})^2\ \theta_0^{\phi}$

On the other hand, if we let $T \to \infty$, [22] reduces to:

[24] $$E_0\left[m_t\right] = m_0 \exp\left(r - \sqrt{B^2 - 4A}\right)t \quad , \; t \ge 0$$

where $m_0 = \frac{1}{4}\phi^2(M_1^I)^2\ \theta_0^{\phi}$

Since $\sqrt{B^2 - 4A} < \sqrt{B^2 - 4AC_{(a)}}$, if the introduction of environmental fees were delayed for ever, $(T = \infty)$, the expected maintenance expenditure pattern would be higher than in the case where the firm is charged from the beginning of the planning horizon, More generally, under our assumptions, the expected maintenance expenditure is positively correlated with T as shown in fig.2:

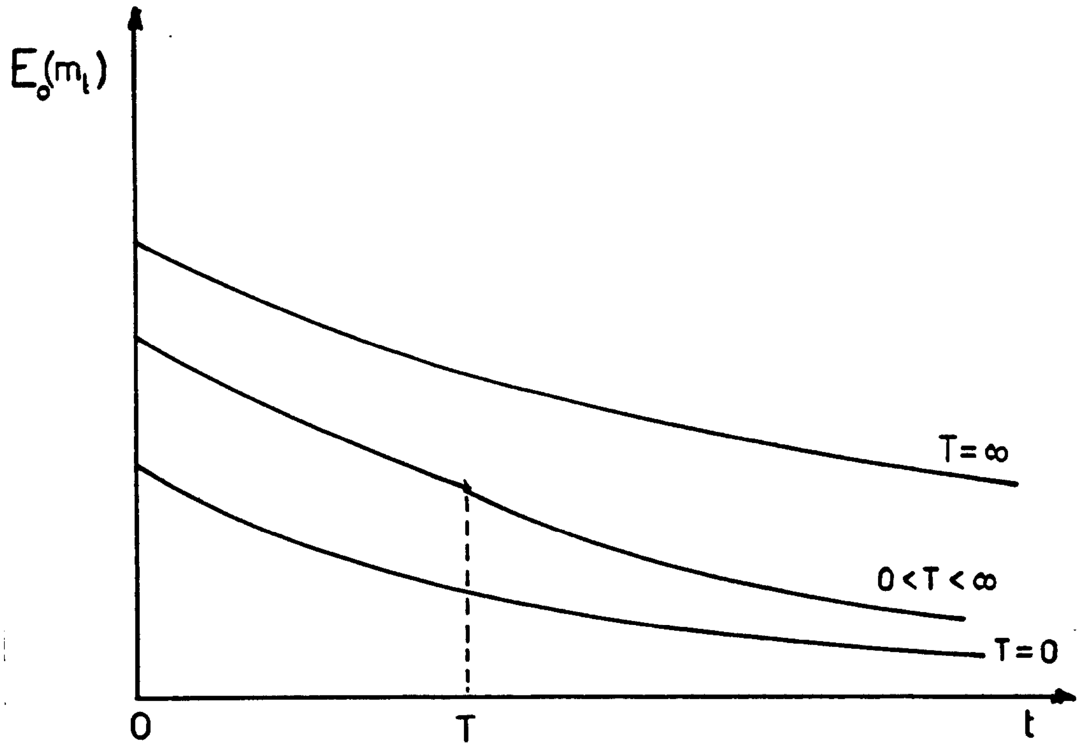

fig.2 Optimal expected maintenance expediture pattern under alternative time profile and $(r < \sqrt{B^2 - 4A})$

3.2.2 Let us now turn to the relationship between T and total expected environmental damage. Total damage attributed to each firm's unit of land is defined as follows:

$$D_{TOT} \equiv D(\theta_t)x_t = \begin{cases} \theta_t^{\phi} & 0 \le t < T \\ (\alpha)^{1/(1-\alpha)} \theta_t^{\phi} & t \ge T \end{cases}$$

Again by applying the **Itô's** Lemma it is possible to derive the expected rate of variation of D_{TOT} , and therefore:

$$[25] \quad E_0\left[D_t x_t \right] = \begin{cases} D_0 x_0 \exp\left(\int_0^t \phi\left[\frac{1}{2}\phi\, M(s;T) - \delta \right] + \frac{1}{2}\phi(\phi-1)\sigma^2 ds \right. & , \; 0 \le t < T \\ E_0(D_T x_T)\exp\left(r - \sqrt{B^2 - 4AC_{(a)}} \right)(t-T) & , \; t \ge T \end{cases}$$

In the case where T = 0, since M(t.;T) = $\dot{M}^{I}$, equation [25] reduces to:

$$[26] \quad E_0\left[D_t x_t \right] = D_0 x_0 \exp\left(r - \sqrt{B^2 - 4AC_{(a)}} \right)t \qquad , \; t \ge 0$$

where $\quad D_0 x_0 = (\alpha)^{1/(1-\alpha)} \theta_0^{\,\phi}$

On the other hand, if we let $T \to \infty$, [25] reduces to:

$$[27] \quad E_0\left[D_t x_t \right] = D_0 x_0 \exp\left(r - \sqrt{B^2 - 4A} \right)t \qquad , \; t \ge 0$$

where $\quad D_0 x_0 = \theta_0^{\,\phi}$

Since, again , $\sqrt{B^2 - 4A} < \sqrt{B^2 - 4AC_{(a)}}$ the expected total damage under $T \to \infty$ will be higher than under T = 0. More generally, under our assumptions, the expected total damage will be positively correlated with T, as shown in fig.3.

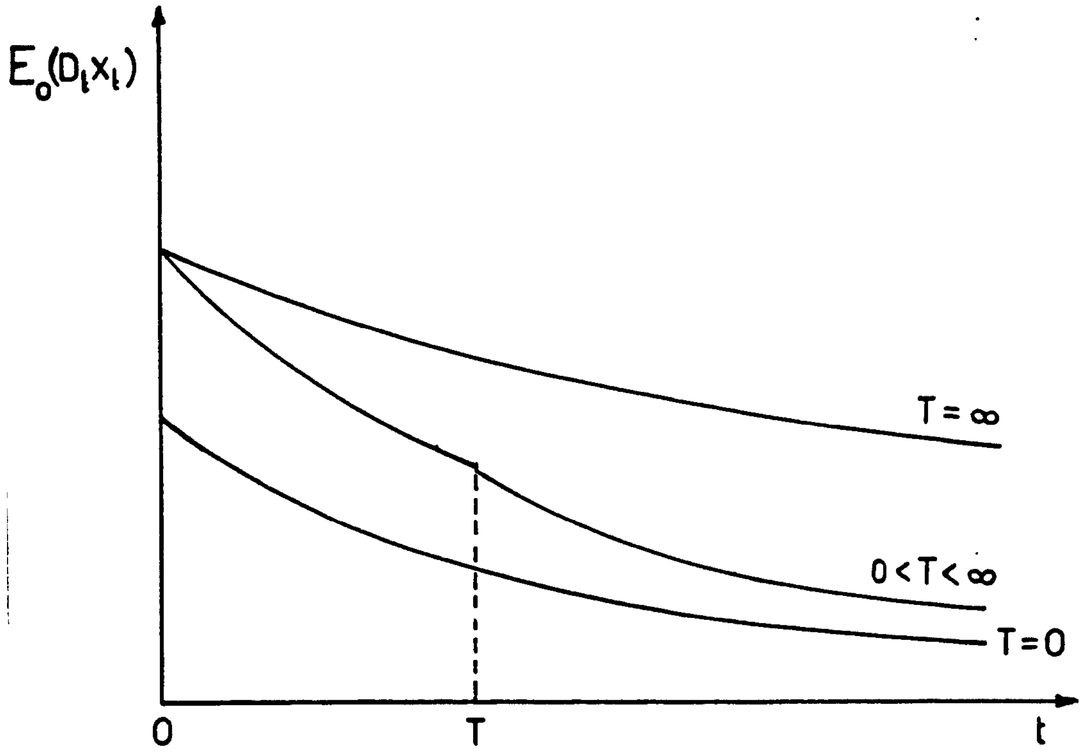

fig.3 **Expected total damage pattern under alternative time profile and** $(r < \sqrt{B^2 - 4A})$

3.2.3 Finally let us consider the effect of uncertainty about future realizations of the soil quality parameter θ on maintenance expenditure, the firm's market value and environmental damage.

According to [14] and [20], maintenance expenditure is an increasing function of M^{II} and M(t;T). This implies that the effect of uncertainty on m can be analyzed by looking at the effect of σ^2 on M^{II}, for $t \geq T$, and on M(t;T) for $0 \leq t < T$.

From [13] and [19], it follows that if $\Phi > 1$ ($0 < \Phi < 1$) an increase of σ^2 leads to an increase (decrease) in M^{II} and in M(t;T). In other words, higher volatility about future realizations of soil quality may either lead to an increase or a decrease in the maintenance expenditure pattern depending on the parameters α, β and ν which make up Φ.

Following the same line of reasoning, the same results apply to the firm's market value.

The effect of uncertainty just described arises from the fact that both the firm's first and second stage instantaneous cash flows, under optimal maintenance expenditure and x use, are convex (concave) functions of θ whenever $\Phi > 1$ ($0 < \Phi < 1$), As a result, increased uncertainty tends to increase (decrease) the value of future cash flows the firm expects to obtain from one unit of land. This, in turn, from the firm's point of view, is equivalent to a reduction (increase) in marginal cost associated with the decision of "improving" soil quality through maintenance expenditure, Or, taking a slightly different perspective, convexity (concavity) of the firm's profit function implies that the disadvantages of expected "bad news", i.e. low future realizations of θ, are more (less) than compensated for by the advantages of "good news", and, the marginal expected profitability of maintenance expenditure increases (decreases).

Let us now analyze the action of uncertainty with regard to the expected environmental damage per unit of land. From [25], [26] and [27], we obtain:

$$\frac{d\ E_0(D_t x_t)}{d\sigma^2} = \begin{cases} > 0 & \text{if } \Phi > 1 \\ < 0 & \text{if } 0 < \Phi < 1 \end{cases}$$

In other words, if, as in fig.3, we assume total damage decreases over time, increased uncertainty may either reduce or increase the expected rate of such decline, depending, again, on the value of the technical parameters which make up Φ.

4. THE AGENCY'S OPTIMAL MANAGEMENT RULES AND THE CHOICE OF OPTIMAL TIME PROFILE FOR ENVIRONMENTAL FEES

4.1 Before trying to characterize the choice of the optimal time profile, let us take T as exogenously given and identify the agency's optimal management rules, in terms of maintenance pattern and x use.

We assume the agency wishes to maximize the following objective function:

$$[28] \quad \max_{m,x} W(\theta_0;T) = E_0\left\{ \int_0^T \Big(Q(x_t,\theta_t) - m_t - D(\theta_t)x_t\Big)e^{-rt}dt + \right.$$

$$\left. + \int_T^\infty \Big(Q(x_t,\theta_t) - m_t - D(\theta_t)x_t + \rho D(\theta_t)x_t\Big)e^{-rt}dt \right\}$$

In other words:

- the agency is assumed to take care of environmental damages over the entire planning horizon $[0,\infty)$;
- the agency's welfare function, which is assumed to be separable in its arguments, includes the firm's utility;
- the agency is assumed to receive a utility from collecting funds through environmental fees, and the parameter ρ ($0 < \rho < 1$) has to be interpreted as the net "social" benefit of such collection.

Adopting a procedure similar to that undertaken in section 3 when dealing with the firm's maximization problem, the agency's optimal variable input level can be obtained:

[29]
$$\begin{cases} x^{*}_{(p)t} = (\alpha)^{1/(1-\alpha)}\ \theta_t^{(\nu+\beta)/(1-\alpha)} & \text{for} \quad 0 \le t < T \\ x^{**}_{(p)t} = \left(\dfrac{\alpha}{1-\rho} \right)^{1/(1-\alpha)}\ \theta_t^{(\nu+\beta)/(1-\alpha)} & \text{for} \quad t \ge T, \quad \rho < \bar{\rho} \\ x^{**}_{(p)t} = \bar{x} & \text{for} \quad t \ge T, \quad \rho \ge \bar{\rho} \end{cases}$$

Moreover, since $0 < \rho < 1$, the following inequality holds: $x^{*}_{(p)t} \le x^{**}_{(p)t}$, for given θ_t. By substituting [29] by [28], and keeping [8], the agency's maximization problem reduces to:

[30]
$$\max_{m} W(\theta_0;T) \equiv E_0\left\{\int_0^T \left[C_{(p)1}\theta_t^{\phi} - m_t\right]e^{-rt}dt + \int_T^{\infty}\left[C_{(p)2}\theta_t^{\phi} - m_t\right]e^{-rt}dt\right\}$$

where $C_{(p)1} \equiv C_{(a)} = (1-\alpha)(\alpha)^{\alpha/(1-\alpha)} < 1$

$$C_{(p)2} = (1-\alpha)\left(\frac{\alpha}{1-\rho} \right)^{\alpha/(1-\alpha)} < 1$$

$$\phi = \frac{1}{1-\alpha}\nu + \frac{\alpha}{1-\alpha}\beta$$

By adopting the same procedure as in section 3, when dealing with the firm's II-stage maximization, and assuming the same restrictions about the parameters ξ, γ and ϕ, the solution for the agency's welfare value at II-stage is:

[31] $$W^{II}(\theta_t) = N^{II}\theta_t^{\phi} \qquad \text{for } t \geq T$$

where $$N^{II} = \frac{B - \sqrt{B^2 - 4AC_{(p)2}}}{2A}$$

$$A = \frac{1}{4}\phi^2$$

$$B = r + \phi\delta - \frac{1}{2}\phi(\phi-1)\sigma^2$$

The agency's optimal maintenance expenditure rule then becomes:

[32] $$m_t = \frac{1}{4}\phi^2 \left[N^{II}\right]^2 \theta_t^{\phi} \qquad \text{for} \quad t \geq T$$

which implies that the stochastic differential equation [2] reduces to:

[33] $$d\theta_t = \left[\frac{1}{2}\phi\, N^{II} - \delta\right]\theta_t dt + \sigma\, \theta_t dz_t \qquad \text{for} \quad t \geq T$$

We can now go on to I-stage maximization, on condition that the agency's welfare value at time T coincides with the discounted scrape value given by [31]. Again following the same procedure adopted in section 3, we obtain:

[34] $W(\theta_t, t; T) = N(t;T)\, \theta_t^{\phi}$ for $0 \le t < T$

where:

$$N(t;T) = \frac{N_2^I - N_1^I \left(\dfrac{N^{II} - N_2^I}{N^{II} - N_1^I} \right) \exp\left(\sqrt{B^2 - 4AC_{(p)1}}\right)(T-t)}{1 - \left(\dfrac{N^{II} - N_2^I}{N^{II} - N_1^I} \right) \exp\left(\sqrt{B^2 - 4AC_{(p)1}}\right)(T-t)}$$

$$N_1^I = \frac{B - \sqrt{B^2 - 4AC_{(p)1}}}{2A}, \quad N_2^I = \frac{B + \sqrt{B^2 - 4AC_{(p)1}}}{2A}$$

It is easy to show that, when t = T, $N(T;T) = N^{II}$. However, unlike what was seen with regards to the firm, in this case :

$$\frac{N^{II} - N_2^I}{N^{II} - N_1^I} < 0$$

In other words, if the agency were able to decide time profile T, it would choose T = 0, because, according to the above inequality its welfare is higher during the period when environmental fees are charged than during the period when firms are exempt from taxation. Obviously, since N^{II} increases with ρ, the higher the net marginal "social" benefit of collecting taxes, the higher is the agency's welfare loss in moving away from T = 0.

Moreover it is easy to obtain from [34]:

$$\lim_{T \to \infty} N(t;T) = N_1^I$$

$$\lim_{T \to 0} N(t;T) = N^{II}$$

with $N_1^I \le N^{II}$, as shown in fig.4.

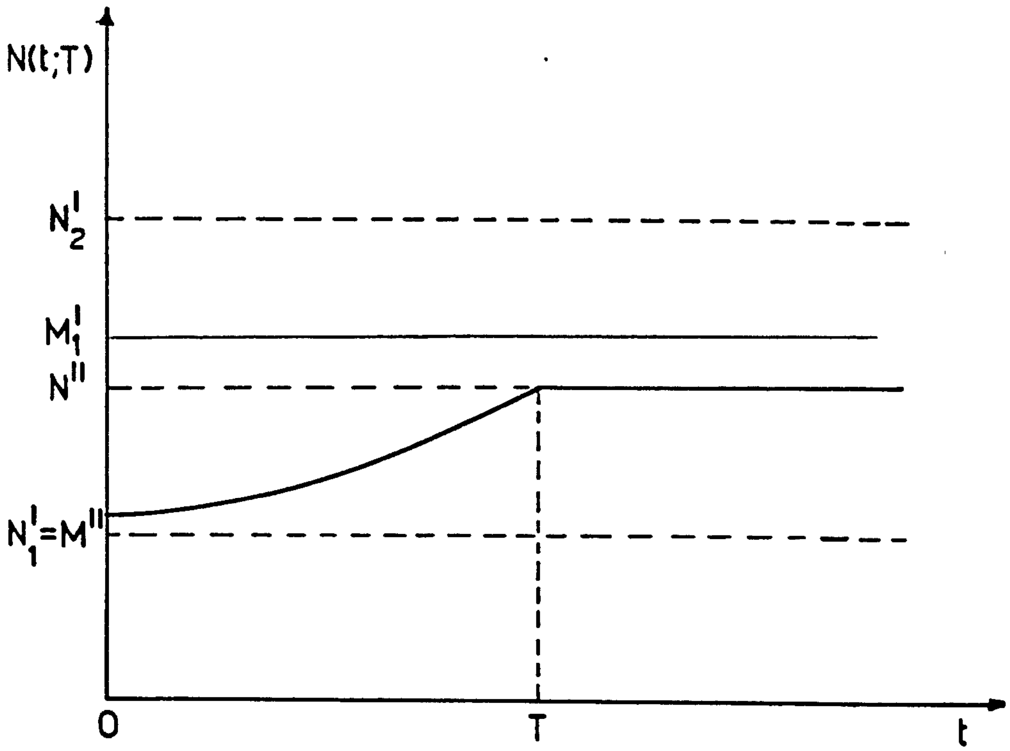

fig.4

The agency's optimal maintenance expenditure policy in the I-stage is described by:

[35] $$m_t = \frac{1}{4}\phi^2 \left[N(t;T) \right]^2 \theta_t^{\phi} \qquad \text{for} \quad 0 \le t < T$$

whilst the stochastic differential equation [2] for θ reduces to:

[36] $$d\theta_t = \left[\frac{1}{2}\phi \, N(t;T) - \delta \right] \theta_t dt + \sigma \, \theta_t dz_t \quad , \text{ for } 0 \le t < T$$

Notice that, by replacing $M(t;T)$ by $N(t;T)$, the same results described in 3.2.1, 3.2.2, and 3.2.3 apply to the agency.

4.2 On the basis of the results proposed in the above sections, we may now consider the problem of optimal choice of T, assuming that this choice is undertaken by the same subject for whom in section 4.1 the optimality conditions for m and x were derived.

In the following discussion it will be assumed that, as far as management decisions are concerned, only two strategies are open to the firm: adoption of its own optimality rules for x and m (described in equations [6], [14] and [18]), or, alternatively, the agency's rules (equations [29], [32] and [35]).

Let us start by summarizing in fig.5 the results obtained in section 3 concerning the relationship between T and the firm's market value (evaluated at the beginning of the planning horizon) and those derived in section 4.1 concerning the relationship between T and the agency's welfare value (evaluated at the beginning of the planning horizon).

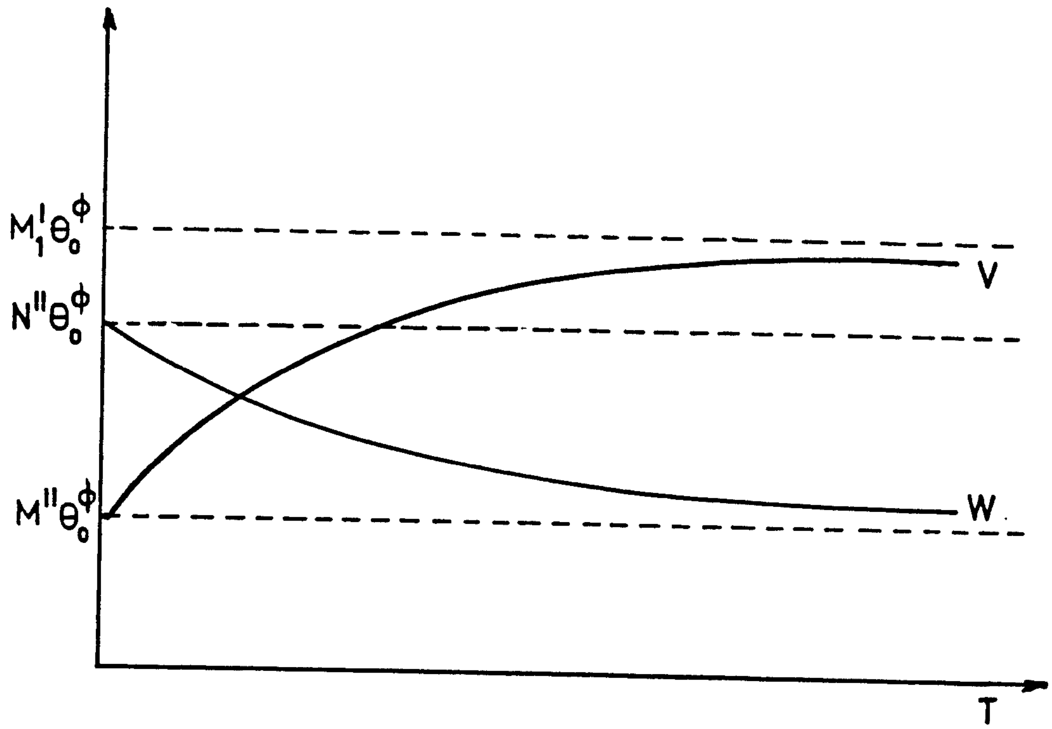

fig.5

From [3] and [28] it can be easily shown that the following identity holds:

$$[37] \qquad V(\theta_0, t=0;T) \equiv W(\theta_0, t=0;T) +$$

$$+ E_0 \left\{ \int_0^T \Big[D(\theta_t)x_t \Big] e^{-rt}dt - \int_T^{\infty} \Big[\rho\ D(\theta_t)x_t\Big] e^{-rt}dt \right\}$$

If the firm adopts the agency's optimal management rules, according to [37], its market value, hereafter $V^P(\theta_0;T)$, becomes equal to the agency's optimal welfare value, described in fig.4, plus the expected value of the difference between discounted social damages in [0,T) and the agency's utility derived from taxation in $[T,\infty)$, which are both evaluated under the agency's optimal rules. On the other hand, if the agency "accepts" the firm's management rules, according to [37] its welfare value, hereafter $W^{a}(\theta_0;T)$, becomes equal to the firm's market value, described in fig.1, minus the expected value of the above difference evaluated, now, under the firm's optimal rules.

Considering the agency's objective function, if it were able to monitor the firm's actions, and if it wanted the firm to adopt the optimal "social" rules, [29], [32] and [35], the best decision would be non-postponement of the introduction of environmental fees. However, if the principal is unable to carry out such monitoring, he has to define an incentive which would induce the agent to self-select the "socially" desired maintenance expenditure pattern and x use. In our framework, this means that the agency has to identify a set of T values which ensure that the firm's market value under the agency's management rules is higher than under its own rules: in this case the time lag granted to firms assumes the meaning of a "premium" they will receive in exchange for accepting the agency's desired management rules. The problem facing the agency consists of picking on, among the set of time profiles which satisfy such a property, the one providing the highest welfare value, T*.

Notice, however, that T* may not be "sustainable" or even optimal for the agency(5). In fact we can take a different perspective and imagine that the firm "offers" the agency, in exchange for acceptance of its own rules, the “opportunity” of setting a different time profile, T^{**}. If T^{**} is “sustainable” and implies a higher welfare value than the one associated with T^{*}, then the agency will find it profitable [6].

To clarify the above statements, let us start by spelling out the firm’s reaction in terms of management decisions to the agency’s announcement of T. Since we assume the firm will choose x and m after this announcement, its best reply function consists of comparing its market value under its own optimal rules, $V(\theta_0;T)$, with $V^P(\theta_0;T)$. That is:

$$[38] \qquad (x,m) = \max \left[V(\theta_0;T) \;,\; V^P(\theta_0;T) \right] \quad \text{for given } T$$

In other words, the firm will adopt its own optimal rules or the agency’s ones depending on which, given T, brings the highest market value.

On the other hand, taking account of the “incentive constraint” [38], the agency will define the optimal time profile by looking at the value of T which makes the welfare value maximum. Formally:

$$[39] \qquad \begin{cases} \max\limits_{T} \left[\max \left(W(\theta_0;T) \;,\; W^a(\theta_0;T) \right) \right] \\ \text{s.t. } [38] \end{cases}$$

In other words, the backward-induction logic requires that the agency foresee that the firm will respond optimally to any time profile announced.

To provide, through a diagrammatic form, a solution for the problem [39], let us preliminary describe the form taken on by the firm's best reply as implied by [38]. In this respect it is possible to identify at least four situations.

Case 1 If the following inequalities hold:

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - AC_{(p)2}} > \rho\left(\frac{\alpha}{1-\rho}\right)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)2}}}$$

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - 4A} < (\alpha)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)1}}}$$

the firm's market value under the agency's optimal rules, V^P, may take, relative to V, the forms depicted in fig.6 (see appendix B):

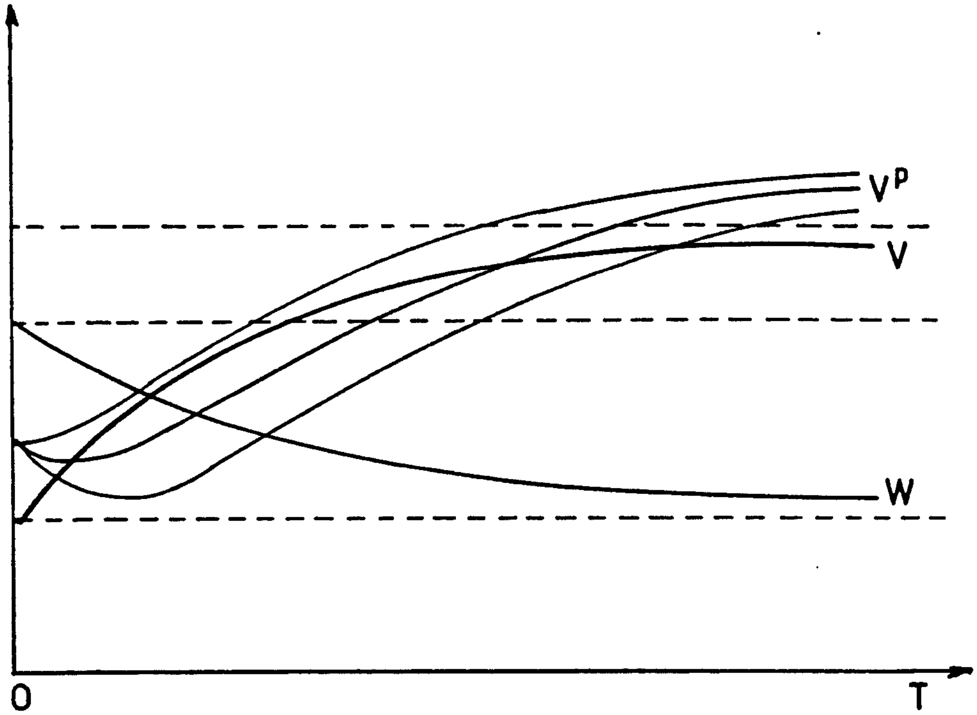

fig.6

It is evident, in this case, that we can have two possible solutions for [38] :

[40] $$V_{max} = V^P \quad , \quad \forall T \quad \Leftrightarrow \quad (x,m) = (x_{(p)}, m_{(p)})$$

or,

[40'] $$V_{max} = \begin{cases} V^P & , \quad T < T_1 \quad \Leftrightarrow \quad (x,m) = (x_{(p)}, m_{(p)}) \\ V & , \quad T_1 < T < T_2 \quad \Leftrightarrow \quad (x,m) = (x_{(a)}, m_{(a)}) \\ V^P & , \quad T > T_2 \quad \Leftrightarrow \quad (x,m) = (x_{(p)}, m_{(p)}) \end{cases}$$

Whether [40] or [40'] represent a solution for the incentive constraint [38] depends on the shape of V^P, which, in turn, depends on the technical parameters related to the production function, damage function and maintenance technology as well as on the net "social" benefit of tax collection ,ρ.

Case 2 If the following inequalities hold:

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - AC_{(p)2}} > \rho\left(\frac{\alpha}{1-\rho}\right)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)2}}}$$

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - 4A} > (\alpha)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)1}}}$$

V^P may take on, relative to V, the forms depicted in fig.7:

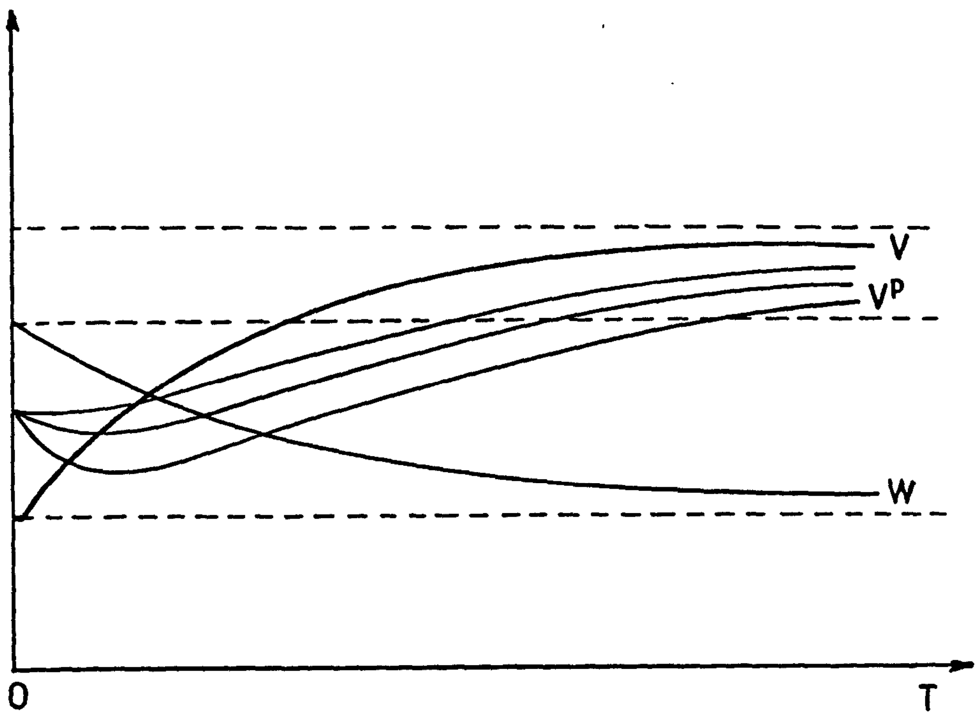

fig.7

In this case, the solution for [38] appears to be:

[41] $$V_{max} = \begin{cases} V^{P} , & T < T_1 \Leftrightarrow (x,m) = (x_{(p)}, m_{(p)}) \\ V , & T > T_1 \Leftrightarrow (x,m) = (x_{(a)}, m_{(a)}) \end{cases}$$

<u>Case 3</u> If the following inequalities hold:

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - AC_{(p)2}} < \rho\left(\frac{\alpha}{1-\rho}\right)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)2}}}$$

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - 4A} < (\alpha)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)1}}}$$

V^P may take, relatively to V, the forms depicted in fig.8:

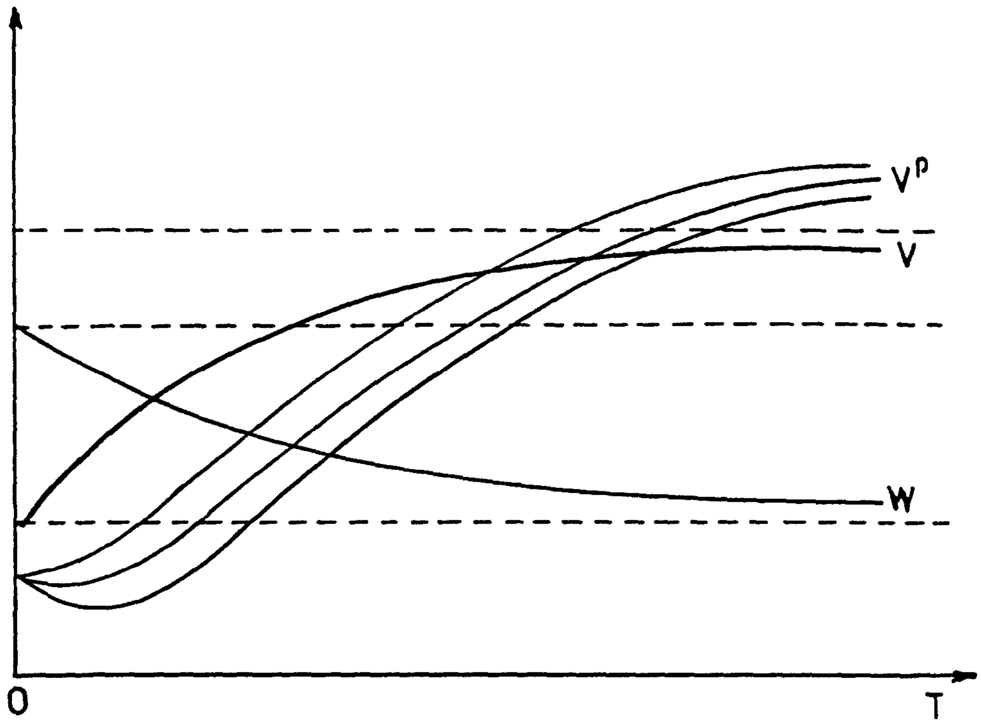

fig.8

In this case, the solution for [38] appears to be:

[42] $$V_{max} = \begin{cases} V \quad , & T < T_1 \iff (x,m) = (x_{(a)}, m_{(a)}) \\ V^p \quad , & T > T_1 \iff (x,m) = (x_{(p)}, m_{(p)}) \end{cases}$$

Case 4 Finally, if the following inequalities hold:

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - AC_{(p)2}} < \rho\left(\frac{\alpha}{1-\rho}\right)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)2}}}$$

$$\sqrt{B^2 - 4AC_{(p)1}} - \sqrt{B^2 - 4A} > (\alpha)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)1}}}$$

V^p may take on, relative to V, the forms depicted in fig.9:

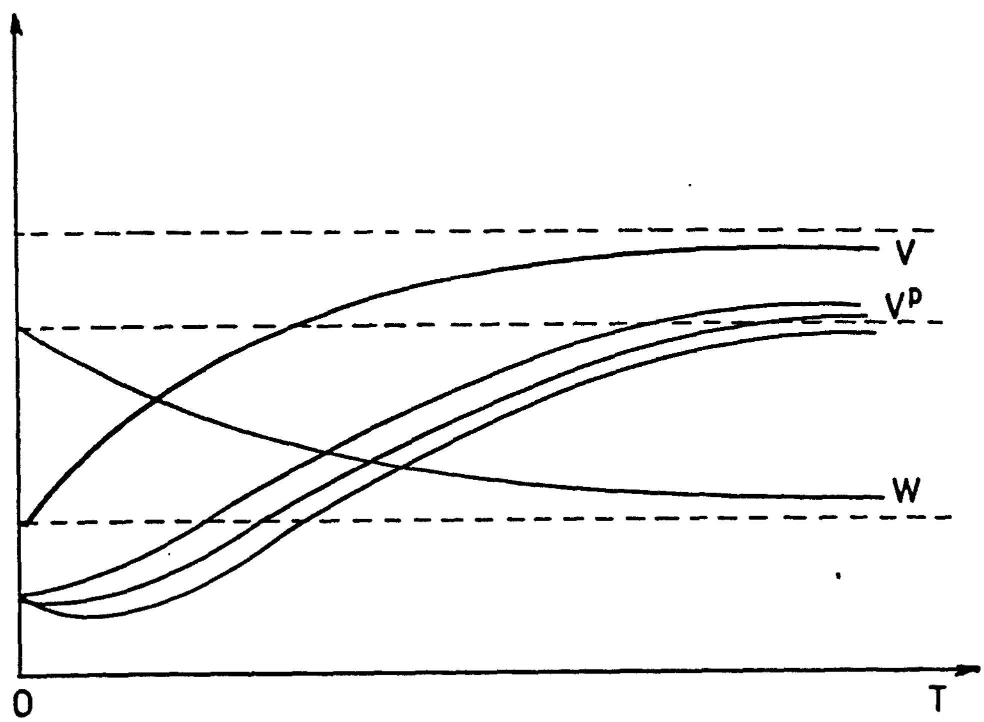

fig.9

In this case, the solution for [38] appears to be:

[43] $V_{max} = V \quad , \quad \forall\, T \quad \Leftrightarrow \quad (x,m) = (x_{(a)},\ m_{(a)})$

To summarize, the solution to incentive constraint [38] may give rise to a variety of situations, which range from the one ([43]) where, whatever time lag is granted, the firm will never find it profitable to give up its own optimal rules, to the one ([40]) where the firm will always find it profitable to "internalize" the agency's rules. There are intermediate situations where the choice of T may affect management decisions by switching the firm's choice from its own rules to the agency's ones, and vice versa ([40'], [41], [42]).

On the grounds of these results, a characterization of some representative solutions for [39] may be obtained by overlaying on fig.6-9 the corresponding agency's welfare value evaluated under its own rules (W) and the firm's ones (W^a). As shown above with reference to the firm's market" value under the agency's rules($x_{(p)}$, $m_{(p)}$), the latter's welfare value, evaluated under ($x_{[a)}$, $m_{(a)}$), may take different shapes, depending, once again, on the parameters of the technical relations considered and on ρ. As a result, a great variety of solutions may be identified. Hereafter, however, we shall merely consider those thought to be sufficiently representative.

Let us start by assuming that the inequalities considered in case 1 hold. Even if W^a may take different shapes, such inequalities imply that as T tends to zero or infinite, W^a becomes lower than W (see appendix B), as shown in figs.10a and 10b where alternative shapes of V^p , picked from fig.6, are also drawn.

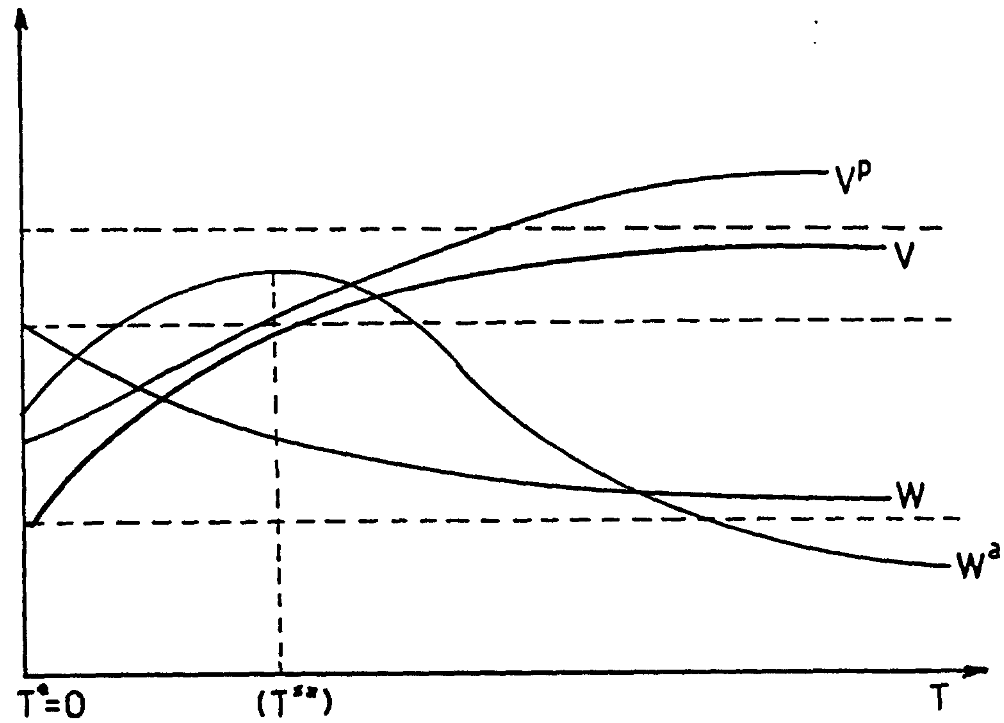

fig.10a

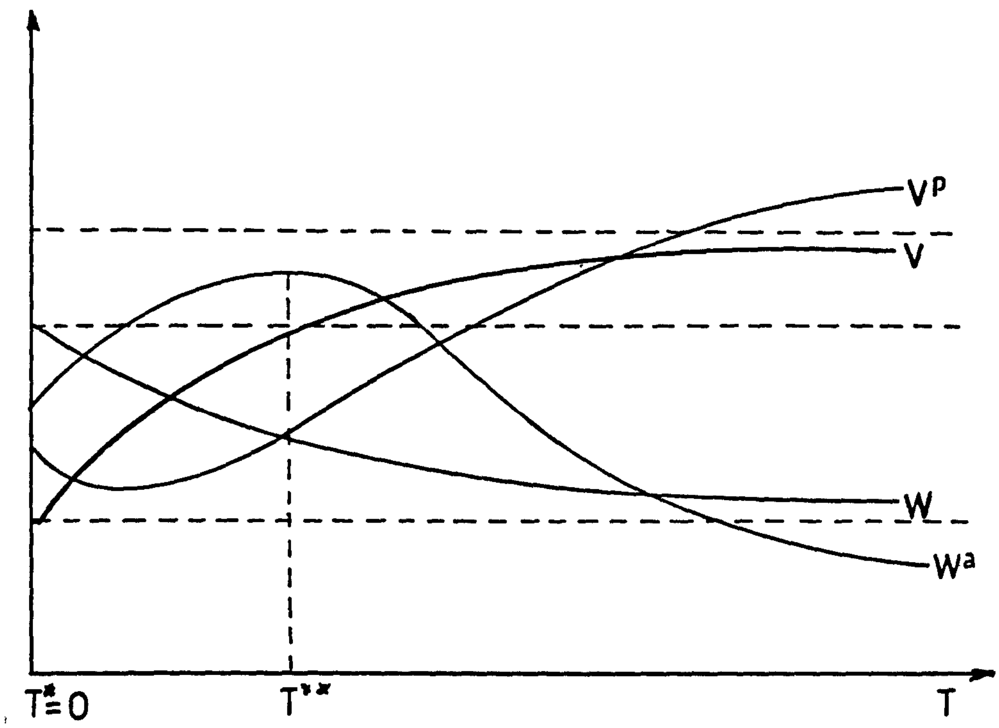

fig.10b

According to fig.10a the highest agency welfare value may be found at T**. However since the firm will always find it profitable to adopt $(x_{(p)}, m_{(p)})$, this time profile is not sustainable. Among the sustainable time profiles, the best choice appears to be non-postponement of the introduction of environmental fees, i.e. $T^* = 0$, On the other hand, if we find ourselves in the situation described by fig.10b, T^{**} appears to be both a sustainable and optimal incentive: therefore, by delaying the introduction of tax payment at date T^{**} and allowing the firm to adopt its own optimal rules, the agency reaches a higher welfare value.

If the inequalities considered in case 2 hold, W^a still becomes lower than W when T tends to zero, whilst it can be either higher or lower than W when T tends to infinite. In figs.11a and 11b two possible shapes of W^a are drawn together with a possible shape of V^p picked from fig.7.

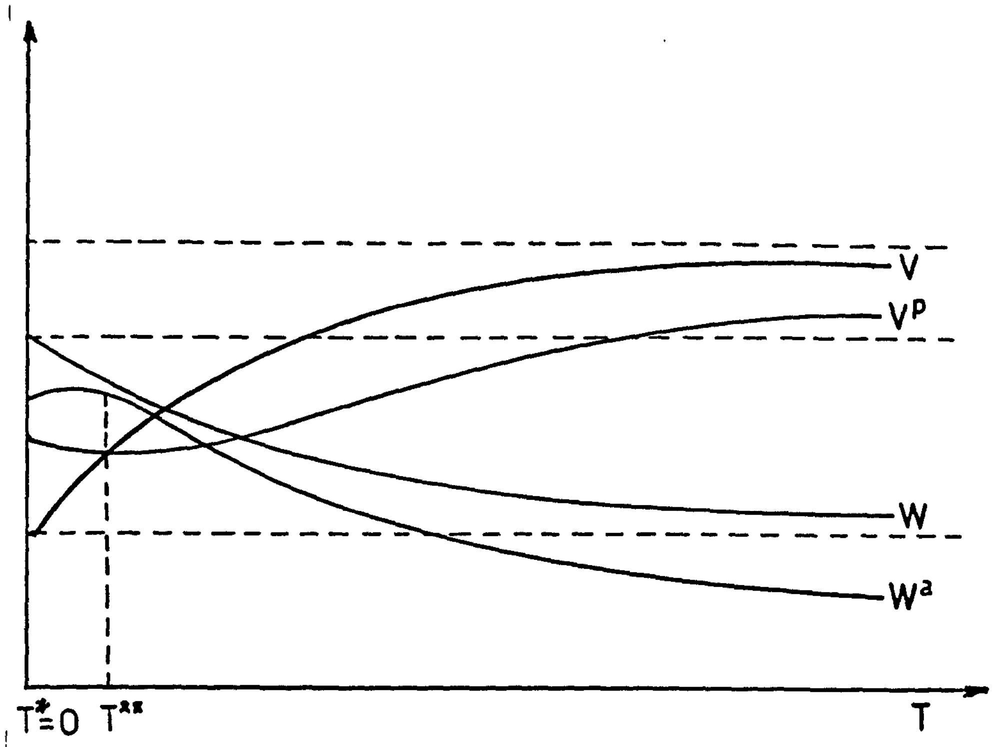

fig.11a

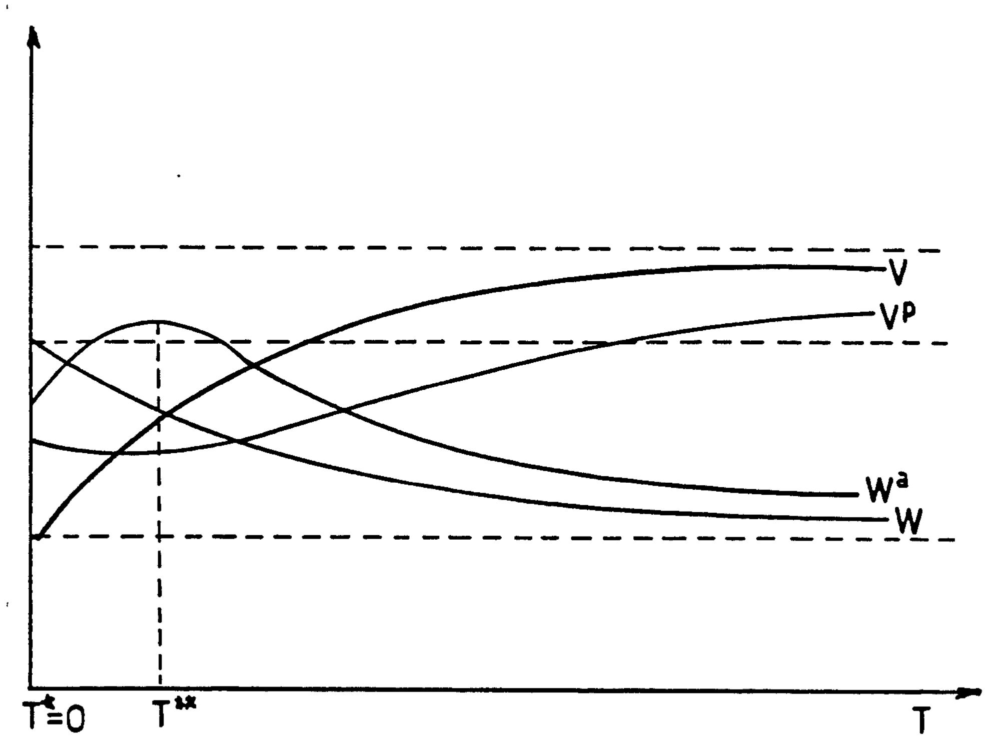

fig.11b

In both situations, figs.11a and 11b, the only sustainable time profile appears to be $T^* = 0$.

If the inequalities considered in case 3 hold, W^a becomes lower than W when T tends to infinite, whilst it can be either higher or lower than W when T tends to zero. In figs.12a, 12b and 12c three possible shapes of W^a are drawn together with a possible shape of V^p picked from fig.8.

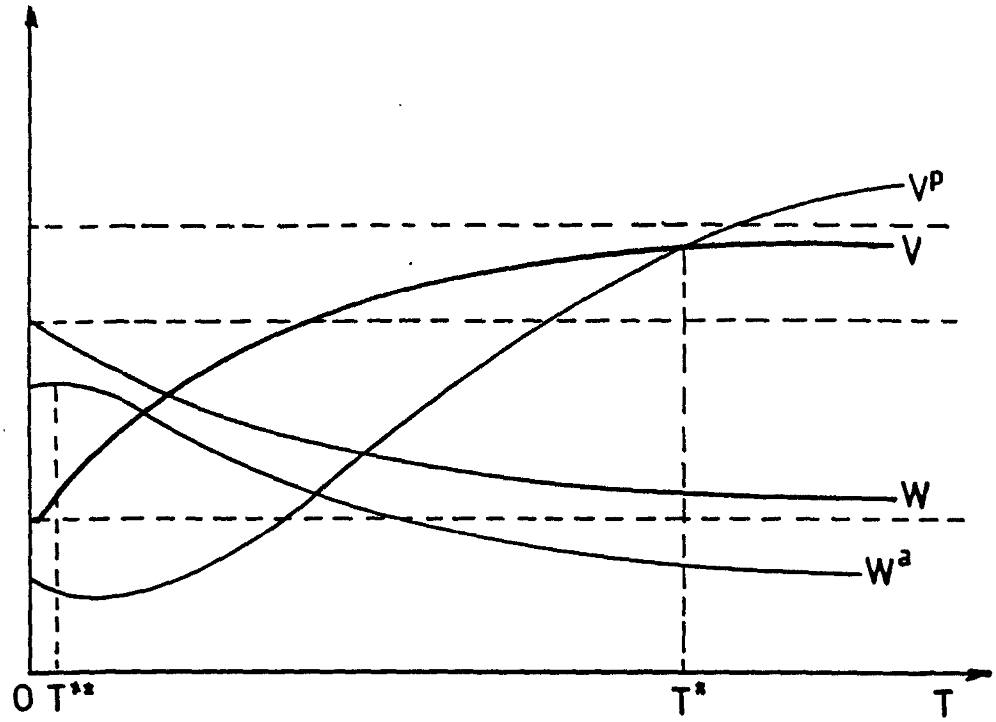

fig.12a

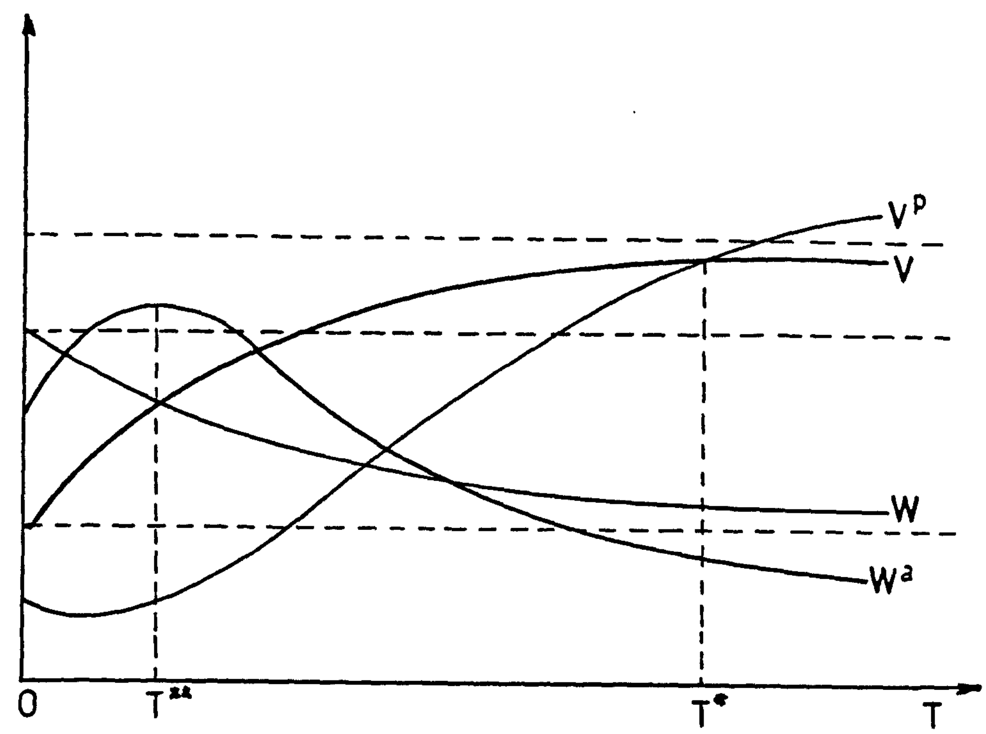

fig.12b

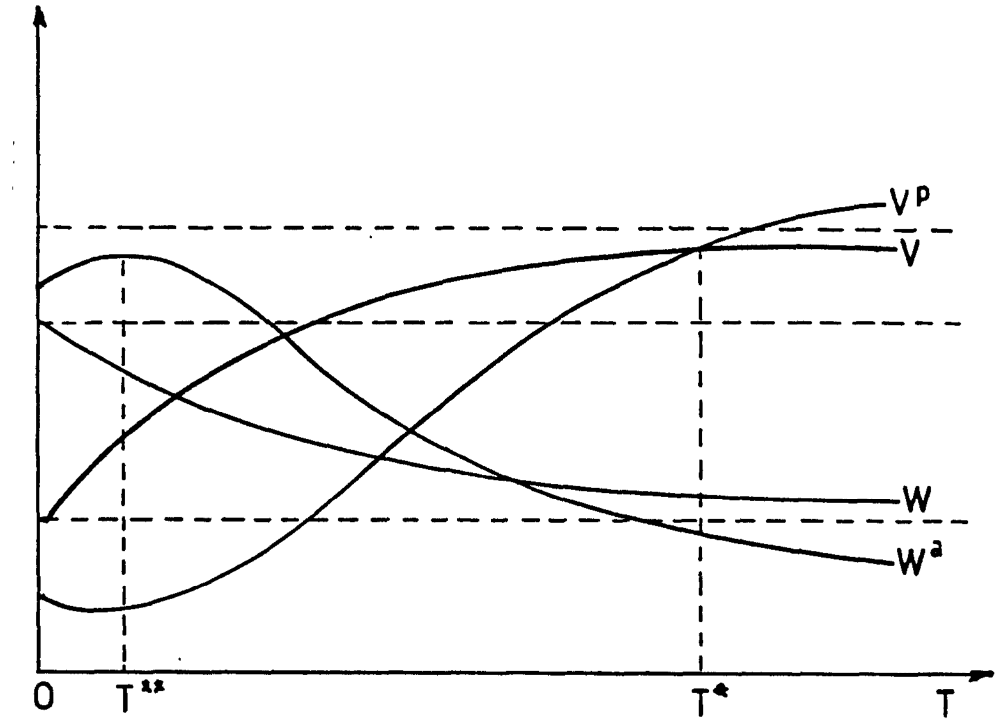

fig.12c

Considering fig. 12a, both T^{**} and T^* are sustainable; however the former, combined with firm's choice $(x_{(a)}, m_{(a)})$, provides the agency with the highest welfare value. On the other hand, in figs.12b and 12c the agency would reach the highest welfare value by non-postponement of the introduction of fees (i.e. $e^{(*)} = 0$), which however is not sustainable: in both situations T^{**} and T^* are sustainable but the former is the best choice for fig.12b, whilst the latter is best for fig.12c. Whilst in the situation depicted in fig.12b the agency finds it convenient to allow the firm to adoptits own rules in exchange for a "short" period of tax exemption, in fig.12c the agency finds it profitable to induce acceptance of the "socially" optimal management rules through a wider period of exemption from payments,

Finally, if the inequalities considered in case 4 hold, W^a can be either higher or lower than W when T tends to zero and infinite. Again, in fig.13a, fig.13b two possible shapes of W^a are drawn together with a possible shape of V^P picked from fig.9,

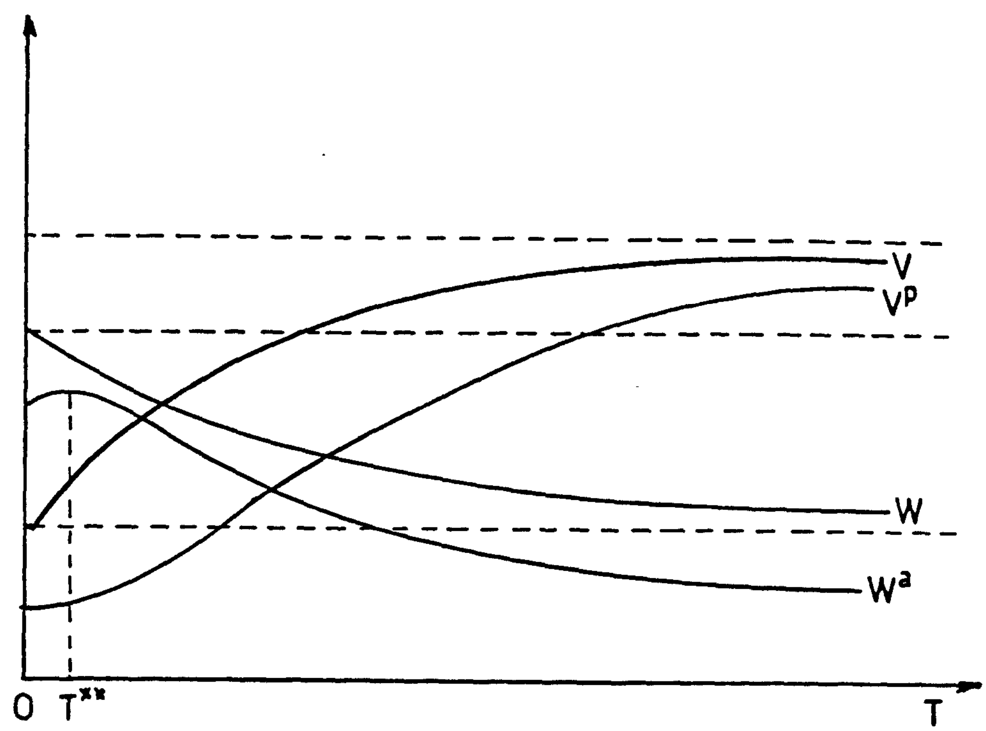

fig.13a

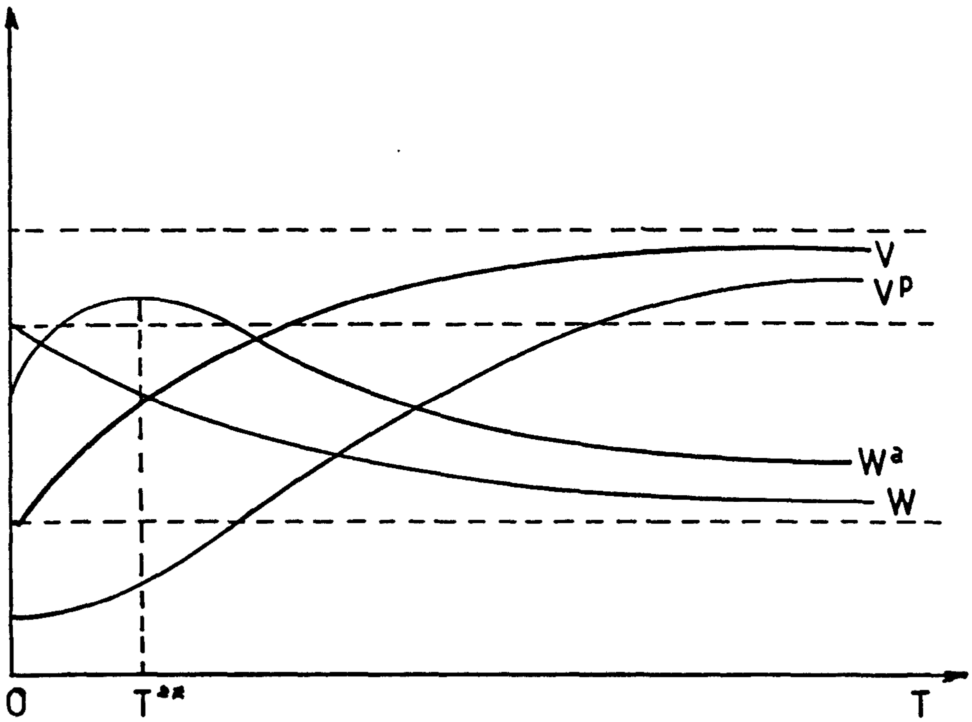

fig.13b

The situation described in fig. 12a may be regarded as symmetrical with respect to the one depicted in fig. 10a: the agency would achieve its highest welfare value at $T^* = 0$, i.e. when no time lag is allowed and the firm adopts as management rules $(x_{(p)}, m_{(p)})$. However, since the firm will never find it profitable to give up its optimal rules, this time profile is not sustainable, therefore, the agency has to look for a T^{**} which makes it better off under $(x_{(a)}, m_{(a)})$. Even in the situation depicted in fig.13b the firm will never find it profitable to adopt $(x_{(p)}, m_{(p)})$. Nevertheless , in this case, the agency’s best choice would be to introduce environmental fees from the beginning of the planning period, i.e. $T^{**} = 0$, since, by doing so, it would achieve a higher welfare value.

5. FINAL REMARKS

The basic aim of the paper was to enhance the results provided in other contributions on NPP control with further insights concerning the role of policy instruments in influencing suspected polluters' productive decisions as well as the allocative properties of alternative regulatory schemes.

In particular we have concentrated on the application of what has been termed an "indirect approach", focusing on two issues which, as far as we know, have received little attention. Firstly, we have tried to deal formally with the possibility that the production site's physical characteristics (the firm's "typology") may vary over time because of non-monitorable actions taken by suspected polluters in conditions of uncertainty regarding the performance of the actions themselves. Secondly, we accounted for the possibility that the legislator might consider the opportunity of delaying the introduction of management practice incentives.

Non-monitorability of the firms' management practices provides the agency with the rationale for selecting the time profile at the beginning of the planning period. Moreover, according to our findings, the decision of delaying the introduction of "environmental fees" may, under certain conditions, constitute an optimal decision from the agency's point of view.

The analysis proposed in the above pages is undoubtedly conditional on a number of assumptions introduced in the paper. These assumptions concern the availability of information regarding maintenance technology, the "form" of uncertainty, the general structure of the technical relationships which make up the model, and the objective functions assigned to the hypothetical actors.

As far as the maintenance technology is concerned, we have assumed that the firm(s) and the agency share the same information as well as the same uncertainty about future realization of the soil quality index. The rationale behind this assumption is that, even if at some point in time the firms are unaware of the maintenance technology, the informational gap could be eliminated by the agency by transmitting all the technical information it possesses before setting the regulatory scheme. Furthermore, if the performance of maintenance decisions is believed to be affected by on-going exogenous shocks, the agency might also include the probability distribution of such shocks in the "informational package".

Turning to the form of uncertainty, it has been assumed that future realizations of the soil quality index will always be uncertain, with a variance which grows linearly with the time horizon. Obviously, this may not always be the case, and the plausibility of modeling the uncertainty along the lines of a Brownian motion process has to be assessed on a case by case basis.

Analogous considerations apply to the assumptions concerning the general structure of the technical relationships introduced in the paper. Moreover, since we deliberately tried to keep the analysis as more general as possible, rather than straightforward conclusions a menu of possible results has been proposed, each of which depends on the values taken by the parameters appearing in the model. It follows that to move a step forward with respect to a merely theoretical analysis would require not only careful assessment of the plausibility of the assumptions concerning the general structure of the technical relationships, but also, a more precise specification of the values taken on by all the relevant parameters.

The set of relevant parameters includes not only those characterizing the technical relationships, but also the net "social" benefit of raising funds through taxation and the rate of discount.

The former was introduced to take account of the possibility that the social planner might receive a utility from taxation as such. In this case, environmental charges not only play the role of instrument for reducing the pressure exerted upon the environment by private economic activities, but are also regarded as means for collecting additional tax revenues. This double role gives rise to a sort of trade-off between environmental quality improvements and increased tax revenues. Depending on the relative weight attached to these two conflicting objectives, different optimal time profiles may arise. Again, the plausibility of assuming the existence, from the agency's point of view, of such a trade-off should be assessed on a case by case basis, but, in our view, it should not be discarded a *priori.*

As far as the second relevant "non technical" parameter, the discount rate, is concerned, it should be noted that we have assumed that the social planner and private agents share the same intertemporal preferences. Since this assumption may appear to be somewhat questionable, an interesting extension of the basic framework we developed consists of exploring the implications of different discount rates in terms of management practice decisions as well as in terms of optimal choice of the time profile for environmental charges.

Further extensions include analysis of the implications on policy design, of abandoning the hypothesis of identical availability of information concerning the initial status of the production site's physical characteristics which are believed to affect the extent of pollutant emissions at field level. Whilst assuming the existence of uninformed agents should not significantly modify our basic framework, in that its main implication is that the firm's reply function has to be defined in terms of expected value according to the probability distribution of θ, the case of an uninformed principal would make the structure of the game much more complex from an analytical point of view. In this case, the analytical framework will take on the form of a true Principal-Agent model, where incentives take on the sense of instruments to extract information from private agents about their initial "typology".

FOOTNOTES

(1) For a discussion of (Itô's) diffusion processes and stochastic differential equations see, for example, Arnold (1974) and Karlin and Taylor (1981). For economic applications of stochastic calculus techniques used throughout the paper, see Malliaris and Brock (1982).

(2) Although w is set equal to zero for technical reasons, it is not so implausible to imagine situations where the price of (potentially) polluting inputs is, relatively speaking, very low or even zero. Examples are nitrogen fertilizers in EEC Countries or nutrients contained in slurry available for farms with mixed crop-livestock production.

(3) In formulating these restrictions we are indebted to the work of Vorst (1987) and Moretto (1991). Notice that $\xi = \frac{1}{2}$ is just in the middle of the domain of ξ and by this restriction we find that the Hamilton-Jacobi-Bellaman equation [11] has only quadratic or linear terms in V_{θ}^{II}. The second restriction is for technical reasons.

(4) Restriction $\gamma = \frac{1}{2}\phi$, introduced in the context of II-stage maximization, together with $\gamma = \frac{1}{2}\varphi$ implies $\phi = \varphi$. Thus, our assumptions imply that the shapes of the firm's cash flow function, gross of maintenance expenditure, at I-stage, and of the firm's cash flow function, gross of m, at II-stage, are the same and differ only by a constant.

(5) In the context of the present paper the term "sustainable" time profile refers to a $T \in [0,\infty)$ which, conditionally on

$$\begin{cases} V(\theta_0;T) > V(\theta_0;T') \\ \text{or} \\ V^p(\theta_0;T) > V^p(\theta_0;T') \end{cases}$$

makes the agency better off, that is:

$$\begin{cases} W^a(\theta_0;T) > W^a(\theta_0;T') \\ \text{or} \\ W(\theta_0;T) > W(\theta_0;T') \end{cases}$$

(6) T^* and T^{**} indicate the sustainable time profiles which make the agency better off under its own optimal rules and under the firm's optimal ones, respectively.

APPENDIX A

This appendix contains a general procedure to find a solution of the control problems presented in the text.

Let $F(\theta_t,t)$ be the maximum of the "value function" (market value for the firm, welfare value for the agency) at time t. If this function is differentiable, then $F(\theta_t,t)$ has to be a solution of the following dynamic programming equation:

$$\text{(A1)} \quad - F_t + rF = \max_m \left[\left(C\, \theta_t^{\phi} - m_t \right) + \left(m_t^{\xi}\, \theta^{-\gamma} - \delta \right) \theta_t\, F_\theta + \frac{1}{2} \sigma^2\, \theta_t^2\, F_{\theta\theta} \right]$$

where F_t, F_θ and Fee are partial derivatives of F with respect to the time and θ.

From the equation (A1) we are able to sum up both the firm optimization at the second stage when F = V^{II}, F_t = 0 and C= $C_{(a)}$, and at the first stage when F = V, C = 1 with the appropriate terminal condition at time T,respectively. Besides setting F = W^{II}, W_t = 0 and C = $C_{(p)2}$ we obtain the agency's optimization at the first stage, and, setting F = W, C = $C_{(p)1}$ and the terminal condition at time T, the agency's optimization at the second stage.

Equation (A1) is known as the Hamilton-Jacobi-Bellman equation of the stochastic version of the optimal control theory.

Differentiating the right-hand side of (A1) with respect to m, we get:

$$\text{(A2)} \qquad m_t = \left(\xi\, F_\theta\, \theta_t^{1-\gamma} \right)^{1/(1-\xi)}$$

Substituting (A2) into A(1) the latter becomes:

$$(A3) \qquad -F_t + rF = C\,\theta_t^{\nu} - \delta\,\theta_t F_\theta + \left(\frac{1-\xi}{\xi}\right) m_t + \frac{1}{2}\sigma^2\theta_t^2\,F_{\theta\theta}$$

Equations (A3) together with (A2) can be expressed as a nonlinear second-order partial differential equation of parabolic type in F, which is solvable under some restrictions on the parameters of marginal productivity of soil quality and of maintenance technology.

Let us start with optimization at the first stage. Assuming $\xi = \frac{1}{2}$ and $\gamma = \frac{1}{2}\,\phi$ the Bellman equation (A3) reduces to:

$$(A4) \qquad F_t - rF + C\,\theta_t^{\phi} - \delta\,\theta_t F_\theta + \frac{1}{4}\theta_t^{2-\phi}\,F_\theta^2 + \frac{1}{2}\sigma^2\,\theta_t^2\,F_{\theta\theta} = 0$$

with the boundary conditions:

$$F(\theta_T;T) = \bar{S}\,\theta_T^{\phi} \qquad , \ \bar{S} > 0 \text{ and constant}$$

$$F(0\ ;t) = 0$$

where $\bar{S}$ stands for the scrape level of the value function at the terminal time T.

A functional form candidate for a solution of this partial differential equation is:

$$(A5) \qquad F(\theta_t,t;T) = S(t;T)\,\theta_t^{\phi}$$

Taking the partial derivatives of (A5) with respect to t and θ yields:

$$(A6.1) \quad F_t = S'(t;T)\,\theta_t^{\phi}$$

$$(A6.2) \quad F_\theta = \phi\,\theta_t^{-1}\,F$$

$$(A6.3) \quad F_{\theta\theta} = \phi(\phi-1)\,\theta_t^{-2}\,F$$

Then the partial differential equation (A4) reduces to the ordinary differential equation:

(A7) $$S'(t;T) = -\frac{1}{4}\phi^2 S^2(t;T) + (r + \delta\phi - \frac{1}{2}\phi(\phi-1)\sigma^2)S(t;T) - C$$

with boundary condition

$$S(T;T) = \bar{S}$$

Setting $A = \frac{1}{4}\phi^2$ and $B = (r+\delta\phi - \frac{1}{2}\phi(\phi-1)\sigma^2)$ the ordinary differential equation (A7) can be rewritten as:

(A8) $$S' = -A S^2 + B S - C$$

(A8) is a Ricatti differential equation, which can be solved by separation of variables. The solution is:

(A9) $$S(t) = \frac{S^{(2)} - S^{(1)}K \exp[A(S^{(1)} - S^{(2)})t]}{1 - S^{(1)}K \exp[A(S^{(1)} - S^{(2)})t]}$$

where the constant K is determined by the boundary condition (A7), and $S^{(1)}$ and $S^{(2)}$ are the solution of the second-order characteristic equation of the r.h.s of (A8), that is:

(A10) $$S^{(1)} = \frac{1}{2A}\left(B - \sqrt{B^2 - 4AC}\right)$$

$$S^{(2)} = \frac{1}{2A}\left(B + \sqrt{B^2 - 4AC}\right)$$

In order for the value F to be positive, at least one of the two constants in (A10) must be positive. Under the hypothesis $B^2 - 4A > 0$, it follows, from the signs of (A10), that $0 < S^{(1)} < S^{(2)}$.

Now imposing the boundary condition (A7) to evaluate the constant K, we get:

$$\text{(A11)} \quad S(t;T) = \frac{S^{(2)} - S^{(1)}\left(\frac{\bar{S} - S^{(2)}}{\bar{S} - S^{(1)}}\right) \exp\left(\sqrt{B^2 - 4AC}\right)(T-t)}{1 - \left(\frac{\bar{S} - S^{(2)}}{\bar{S} - S^{(1)}}\right) \exp\left(\sqrt{B^2 - 4AC}\right)(T-t)}$$

It easy to check, from (A11), that $S^{(1)}$ is a locally asymptotically stable level of maximal expected discounted value if we let the horizon time T approach to infinite. In other words, letting T tend to infinite, the scrape value disappears and the root $S^{(1)}$ is necessary and sufficient for the value function F, i.e. the expected discounted flow of profit, to converge.

Finally the optimal expected value function can be written as (A5) with S(t;T) given by (A11).

Considering now the maximization at the second stage it is immediate to note that, since the horizon goes from T to infinite, it becomes time homogeneous? i.e. the scrape value is equal to zero and $F_t = 0$. The (A8) is no longer a differential equation but only a second-order characteristic equation in S, which gives two distinct roots as in (A10), Recalling that only $S^{(1)}$ **guarantees** the existence of F , the optimal expected value function will be as in (A5) with S(t;T) constant and equal to $S^{(1)}$.

Finally, it should be noted that with a stochastic differential equation such as [2] in the text, with $f(m,\theta)$ given by [81, there might be a positive probability that the process $\{\theta_s\}$ becomes zero (negative) or even infinite. On this matter Vorst (1987) and Moretto (1991) showed that under the optimal maintenance policy this probability is zero for the cases under analysis. In other words, the left boundary (zero) and the right boundary (infinite) are not attracting for the process $\{\theta_s\}$, at least in a finite expected time. In the rest of the paper we refer to this result in guaranteeing the necessary and sufficient conditions for the firm's value function [3], and the agency's welfare function [27] to exist (i.e. to be bounded).

APPENDIX B

From identity [37], if the r.h.s. is evaluated under the agency's management optimal rules, we get, at the beginning of the planning period:

$$\text{(B1)} \quad V^P(\theta_0;T) = W(\theta_0;T) + E_0\left\{ \int_0^T D_t x^*_{(p)t} e^{-rt} dt - \int_T^\infty \rho D_t x^{**}_{(p)t} e^{-rt} dt \right\}$$

where $\{\theta_t\}$ evolves according to [36] in $[0,T)$ and to [33] in $[T,\infty)$.

Since, as indicated in the text the following limits hold:

$$\lim_{T\to\infty} N(t;T) = N_1^I$$

$$\lim_{T\to 0} N(t;T) = N^{II}$$

it is possible to verify that, if T = 0:

$$\text{(B2)} \quad V^P(\theta_0;T=0) = N^{II}\ \theta_0^{\ \phi} - E_0\left\{ \int_0^\infty \rho D_t x^{**}_{(p)t} e^{-rt} dt \right\}$$

$$= \left[\frac{B - \sqrt{B^2 - 4AC_{(p)2}}}{2A} - \rho\left(\frac{\alpha}{1-\rho}\right)^{1/(1-\alpha)} \frac{1}{\sqrt{B^2 - 4AC_{(p)2}}} \right] \theta_0^{\ \phi}$$

whilst, if T = ∞ :

(B3) $$V^P(\theta_0;T=\infty) = {}_1N^I\ \theta_0^{\phi} + E_0\left\{\int_0^{\infty} D_t x^*_{(p)t} e^{-rt}dt\right\}$$

$$= \left[\frac{B-\sqrt{B^2-4AC_{(p)1}}}{2A} + (\alpha)^{1/(1-\alpha)}\frac{1}{\sqrt{B^2-4AC_{(p)1}}}\right]\theta_0^{\phi}$$

Equations (B2) and (B3) allow us to examine the trends of (B1) when T tends to zero or infinite. Recalling that $V(\theta_0;T) = M(0;T)\theta_0^{\phi}$, if $T = 0$:

$$V^P(\theta_0;T=0) \gtrless V(\theta_0;T=0)$$

$$\Leftrightarrow$$

$$\sqrt{B^2-4AC_{(a)}} - \sqrt{B^2-4AC_{(p)2}} \gtrless \rho\left(\frac{\alpha}{1-\rho}\right)^{1/(1-\alpha)}\frac{2A}{\sqrt{B^2-4AC_{(p)2}}}$$

whilst if $T = \infty$:

$$V^P(\theta_0;T=\infty) \gtrless V(\theta_0;T=\infty)$$

$$\Leftrightarrow$$

$$\sqrt{B^2-4AC_{(p)1}} - \sqrt{B^2-4AC} \lessgtr (\alpha)^{1/(1-\alpha)}\frac{2A}{\sqrt{B^2-4AC_{(p)1}}}$$

Since $C_{(a)} = C_{(p)1}$, by combining the above inequalities, we get the four situations described in the text.

To analyze the behavior of (B1) in the interval $[0,\infty)$ we can take the first and second derivative with respect to T. The first derivative yields:

(B4) $$\frac{dV^P}{dT} = \frac{dW}{dT} + e^{-rT}(1+\rho)\ E_0\left(D_T\ x^{**}_{(p)T}\right)$$

Since $\frac{dW}{dT} < 0$, and $E_0\left(D_T x^{**}_{(p)T}\right)$ is positive, the sign of (B4) is not determined a priori. Moreover, notice that (B4) describes the "trade-off" between the firm's marginal loss when T increases, evaluated according to the agency welfare function, and the expected marginal benefit the firm will receive, in terms of reduced tax payments, when the introduction of fees is delayed.

Taking the second derivative we obtain:

$$\text{(B5)}\quad \frac{d^2V^P}{dT^2} = \frac{d^2W}{dT^2} - re^{-rT}(1+\rho)E_0\left(D_T\, x^{**}_{(p)T}\right) + e^{-rT}(1+\rho)E_0\left(\frac{d(D_T x^{**}_{(p)T})}{dT}\right)$$

where:

$$\frac{d^2W}{dT^2} = \frac{1+Ke^{(\sqrt{B^2-4AC_{(p)1}})T}}{1-Ke^{(\sqrt{B^2-4AC_{(p)1}})T}}\sqrt{B^2-4AC_{(p)1}}\ \frac{dW}{dT} > 0$$

$$K = \frac{N^{II}-N^{I}_{2}}{N^{II}-N^{I}_{1}} = -\frac{\sqrt{B^2-4AC_{(p)1}}+\sqrt{B^2-4AC_{(p)2}}}{\sqrt{B^2-4AC_{(p)1}}-\sqrt{B^2-4AC_{(p)2}}} < -1$$

$$E_0\left(\frac{d(D_T x^{**}_{(p)T})}{dT}\right) = \left[r - \int_0^T \frac{1}{2}\phi^2 \frac{dN(t;T)}{dT}dt - \sqrt{B^2-4AC_{(p)2}}\right]E_0\left(D_T\, x^{**}_{(p)T}\right)$$

The last expression is derived from [241 substituting N(t;T) instead of M(t;T). Considering that $\frac{dN(t;T)}{dT} < 0$, it iseasy to check that as T tends to zero the second derivative can be positive, whilst as T tends to infinite, it becomes negative. In other words, depending on the value assumed by the technical parameters V^P may be downward sloping and convex when T is close to zero and upward sloping and concave as T increases, with a minimum given by $\frac{dV^P}{dT} = 0$, as shown in the text.

In the same way, from [37] we can obtain the welfare function evaluated under the firm's rules:

(B6) $$W^a(\theta_0;T) = V(\theta_0;T) - E_0\left\{ \int_0^T D_t x^*_{(a)t} e^{-rt} dt - \int_T^\infty \rho D_t x^{**}_{(a)t} e^{-rt} dt \right\}$$

where $\{\theta_t\}$ evolves according to [21] in [0,T) and to [15] in $[T,\infty)$.

Again taking account of the following limits:

$$\lim_{T\to\infty} M(t;T) = M_1^I$$

$$\lim_{T\to 0} M(t;T) = M^{II}$$

it is possible to verify that, if T = 0:

B7) $$W^a(\theta_0;T=0) = M^{II}\,\theta_0^{\phi} + E_0\left\{ \int_0^\infty \rho D_t x^{**}_{(a)t} e^{-rt} dt \right\}$$

$$= \left[\frac{B-\sqrt{B^2-4AC_{(a)}}}{2A} + \rho(\alpha)^{1/(1-\alpha)} \frac{1}{\sqrt{B^2-4AC_{(a)}}} \right]\theta_0^{\phi}$$

hilst, if T = ∞ :

B8) $$W^a(\theta_0;T=\infty) = M_1^I\,\theta_0^{\phi} - E_0\left\{ \int_0^\infty D_t x^*_{(a)t} e^{-rt} dt \right\}$$

$$= \left[\frac{B-\sqrt{B^2-4A}}{2A} - \frac{1}{\sqrt{B^2-4A}} \right]\theta_0^{\phi}$$

Equations (B7) and (B8) allow us to examine the trends of (B6) when T tends to zero or infinite. Recalling that $(\theta_0;T) = N(0;T)\theta_0^{\phi}$, if T = 0:

$$W^a(\theta_0;T=0) \gtrless W(\theta_0;T=0)$$

$$\Leftrightarrow$$

$$\sqrt{B^2 - 4AC_{(a)}} - \sqrt{B^2 - 4AC_{(p)2}} \lessgtr \rho(\alpha)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(a)}}}$$

whilst if T = ∞:

$$W^a(\theta_0;T=\infty) \gtrless W(\theta_0;T=\infty)$$

$$\Leftrightarrow$$

$$\sqrt{B^2 - 4AC_{(a)}} - \sqrt{B^2 - 4A} \gtrless \frac{2A}{\sqrt{B^2 - 4A}}$$

Moreover, since:

$$\rho\left(\frac{\alpha}{1-\rho}\right)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(p)2}}} > \rho(\alpha)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(a)}}}$$

$$(\alpha)^{1/(1-\alpha)} \frac{2A}{\sqrt{B^2 - 4AC_{(a)}}} < \frac{2A}{\sqrt{B^2 - 4A}}$$

Confronting the above inequalities with those of V^P and V, we get the four cases shown in figs. 9-12.

Finally, to analyze the behavior of (B6) within the interval $[0.\infty)$ we take the first and second derivative with respect to T. The first yields:

$$(B) \quad \frac{dW^a}{dT} = \frac{dV}{dT} - e^{-rT}(1+\rho)\, E_0\left(D_T\, x^{**}_{(a)T}\right)$$

Since $\frac{dV}{dT} > 0$, and $E_0\left(D_T x^{**}_{(a)T}\right)$ is positive, the sign of (B9) is not determined a priori. The first term on the r.h.s. represents the agency's marginal gain when T increases, evaluated according to the firm's value function. The second term, in turn, is the expected marginal loss the agency will incur, in terms of reduced tax payments, when the introduction of fees is delayed.

Taking the second derivative we obtain:

$$\text{(B10)} \quad \frac{d^2W^a}{dT^2} = \frac{d^2V}{dT^2} + re^{-rT}(1+\rho)E_0\left(D_T\ x^{**}_{(a)T}\right) - e^{-rT}(1+\rho)E_0\left(\frac{d(D_T x^{**}_{(a)T})}{dT}\right)$$

where:

$$\frac{d^2V}{dT^2} = \frac{1+K'e^{(\sqrt{B^2-4AC_{(a)}})T}}{1-K'e^{(\sqrt{B^2-4AC_{(a)}})T}}\sqrt{B^2-4AC_{(a)}}\ \frac{dV}{dT} < 0$$

$$K' = \frac{M^{II}-M^I_2}{M^{II}-M^I_1} = -\frac{\sqrt{B^2-4AC_{(a)}}+\sqrt{B^2-4A}}{\sqrt{B^2-4A}-\sqrt{B^2-4AC_{(a)}}} > 1$$

$$E_0\left(\frac{d(D_T x^{**}_{(a)T})}{dT}\right) = \left[r - \int_0^T \frac{1}{2}\phi^2 \frac{dM(t;T)}{dT}dt - \sqrt{B^2-4AC_{(a)}}\right] E_0\left(D_T\ x^{**}_{(a)T}\right)$$

where the last expression is derived from [24]. Considering that $\frac{dM(t;T)}{dT} > 0$, it is easy to check that as T tends to zero the second derivative can be negative, whilst as T tends to infinite, it becomes positive. In other words, depending on the value assumed by the technical parameters, W^a may be upward sloping and concave when T is close to zero and downward sloping and convex as T increases, with a maximum given by $\frac{dW^a}{dT} = 0$, as shown in the text.

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